OpenMHD: Godunov-type code for magnetic reconnection and MHD problems

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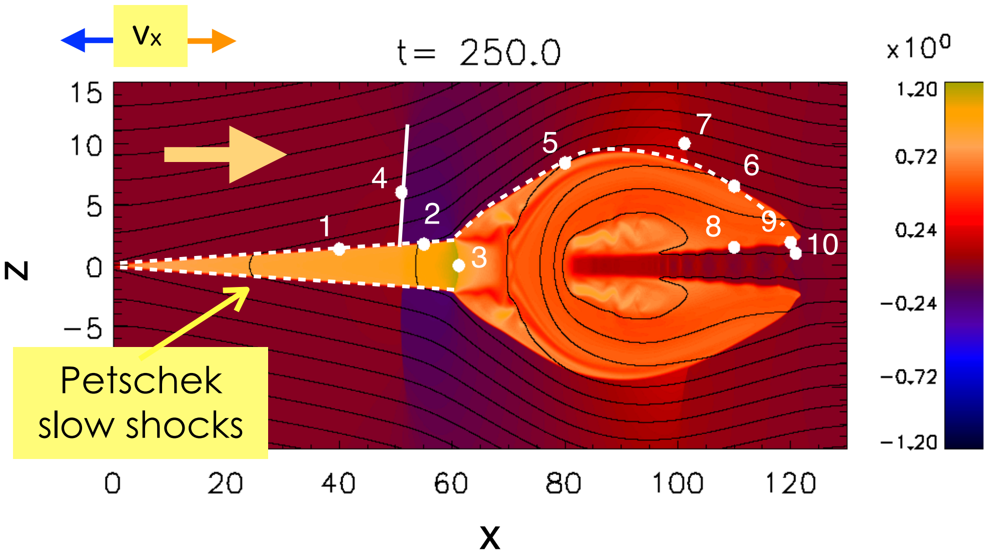
[1] Zenitani, *Phys. Plasmas* **22**, 032114 (2015)

[2] Zenitani, *Astrophysics Source Code Library*, ascl:1604.001 (2016)

MHD shocks in reconnection



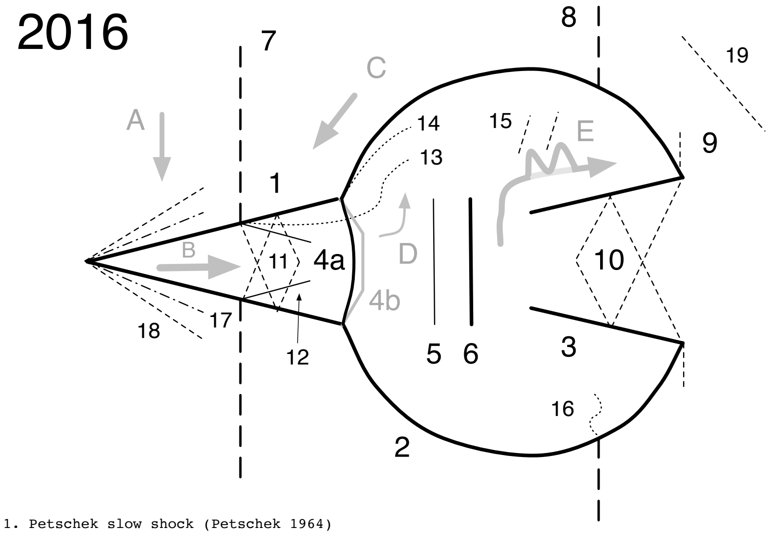


TABLE I. Rankine–Hugoniot analysis. The subscripts 1 and 2 denote the upstream and downstream quantities. The locations (x, z) in the simulation domain [see also Fig. 1(b)], the shock normal vector $\hat{\boldsymbol{n}}$, the shock velocity v_{sh}, the angle between $\hat{\boldsymbol{n}}$ and the upstream magnetic field $\boldsymbol{B}_1$, the upstream plasma beta, flow Mach numbers to fast, intermediate (Alfvén), and slow-mode speeds, and the temperature ratio. The asterisk sign (*) indicates unreliable results (see Sec. III F). The letter (S) indicates a slow shock, (F) is a fast shock, and (U) is unclassified.

No.	Location	(n_x, n_z)	v_{sh}	$\lvert\theta_{BN}\rvert$	β_1	$\mathcal{M}_{f1}$	$\mathcal{M}_{i1}$	$\mathcal{M}_{s1}$	$\mathcal{M}_{f2}$	$\mathcal{M}_{i2}$	$\mathcal{M}_{s2}$	T_2/T_1	
1	(40.0, 1.35)	(−0.03, 1.00)	0.0	86.3	0.22	0.06	0.98	2.49	0.04	0.69	0.69	2.72	(S) Petschek shock
2	(55.0, 1.75)	(−0.04, 1.00)	−0.013	86.3	0.098	0.06	0.88	3.22	0.04	0.58	0.58	4.58	(S) Petschek shock
3	(61.2, 0)	(−1.00, 0.00)	−0.40	90	303	1.41			0.77			1.38	(F) Reverse shock
4	(51.0, 6.0)	(1.00, −0.04)	0.31	9.4	0.12	0.41	0.42	1.34	0.33	0.34	0.78	1.33	(S) Postplasmoid vertical shock
5	(80.0, 8.4)	(−0.18, 0.98)	−0.06	86.5	0.16	0.05	0.85	2.47	0.03	0.56	0.65	2.54	(S) Outer shell
6	(110.0, 6.5)	(0.24, 0.97)	0.19	84.9	0.21	0.06	0.76	1.99	0.05	0.53	0.64	2.06	(S) Outer shell
7	(101.2, 10.0)	(0.94, 0.33)	0.54	25.2	0.23	0.43	0.49	1.15	0.39	0.44	0.87	1.15	(S) Forward vertical shock
8	(110.0, 1.5)	(−0.06, −1.00)	0.10	87.8	1.1	0.12	4.5*	6.5*	0.12	3.9*	4.0*	1.55	(U) Intermediate shock?
9	(120.0, 1.9)	(0.13, −0.99)	0.13	87.1	0.49	0.09	2.0*	3.8*	0.08	1.7*	1.9*	1.86	(U) Slow shock?
10	(120.9, 1.0)	(0.64, −0.77)	0.50	46.8	2.63	1.22	3.00	3.40	0.88	2.66	3.06	1.18	(F) Oblique shock

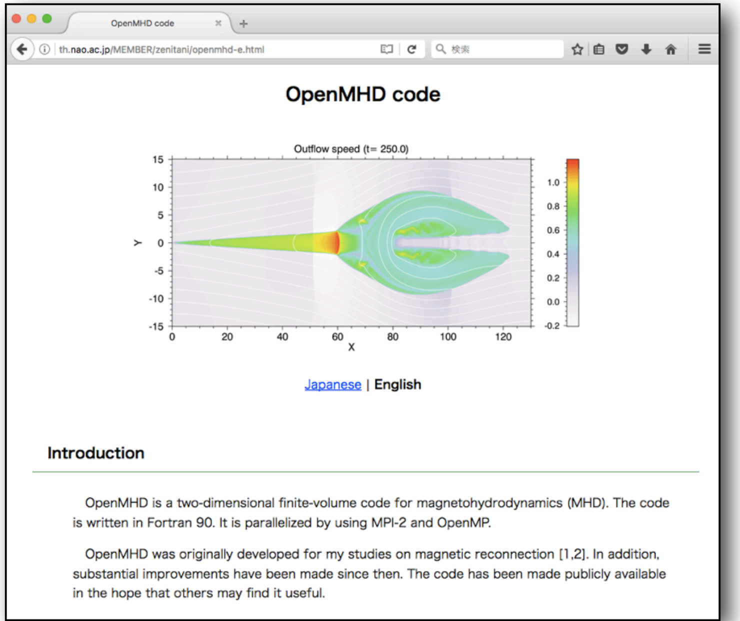
1. Petschek slow shock (Petschek 1964)
2. outer shell = slow shock (Ugai 1995)
3. intermediate shock (Abe & Hoshino 2001) or slow shock (Saito et al. 1995)
4a fast shock (Forbes & Priest 1983)
4b oblique shock & Mach disk (Takasao et al. 2015)
5. looptop front (Ugai 1987)
6. tangential discontinuity
7. post-plasmoid vertical slow shock (Zenitani et al. 2010)
8. outer vertical slow shock (Zenitani & Miyoshi 2011)
9. fast-mode wave front (Saito et al. 1995)
10. overexpanded shock-diamonds (Zenitani et al. 2010)
11. underexpanded shock-diamonds (Zenitani 2015)
12. slow expansion wavefront (Zenitani 2015)
13. contact discontinuity (Zenitani & Miyoshi 2011, 2015)
14. contact discontinuity (Zenitani 2015)
15. vortex-driven shocklets (Miura 1992, 1995)
16. contact discontinuity (Zenitani 2015)

17. rotational discontinuity [in guide-field reconnection] (Petschek & Thorne 1967)
18. conduction front [with heat conduction] (Yokoyama & Shibata 1997)
19. forward head shock [in asymmetric reconnection] (Nitta et al. 2016)

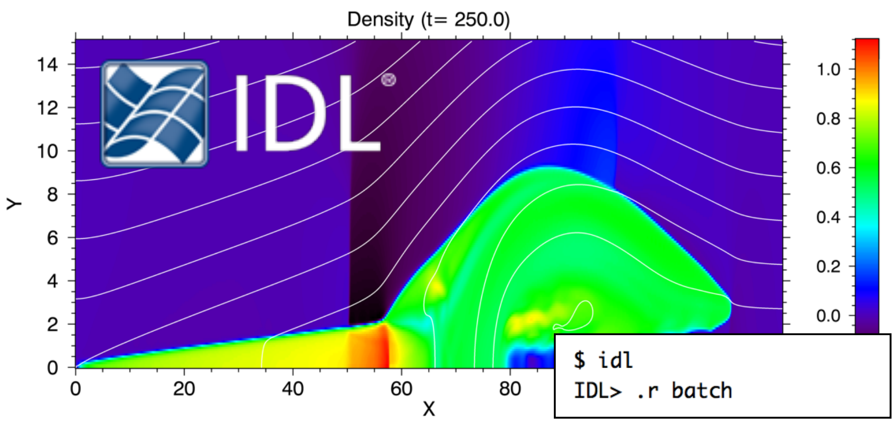
A. reconnection inflow
B. outflow jet
C. post-plasmoid reverse flow
D. internal flow
E. flapping jet (KH instability)

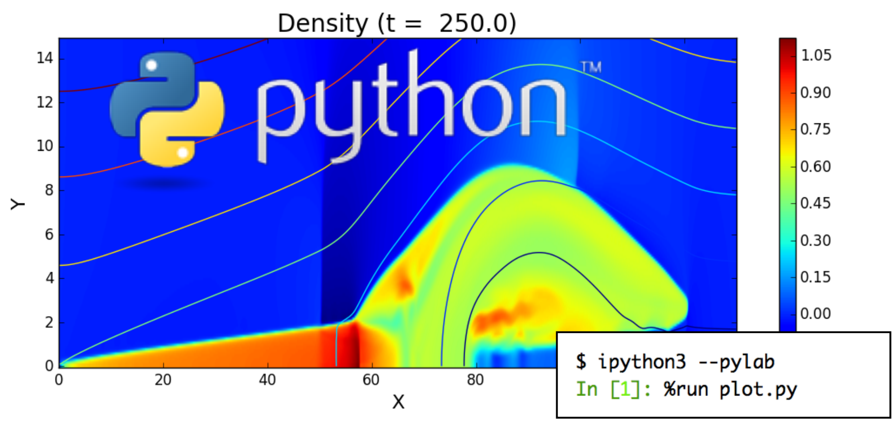
Zenitani & Miyoshi 2011
Zenitani 2015

OpenMHD - public code



- MHD code by Zenitani & Miyoshi (2011, 2015) with recent improvements
- Fortran 90, 2D (Internally 3D), HLLD, MUSCL, MPI+OpenMP, MPI-IO, GPU (CUDA)
- Visualization code in IDL and Python3 (matplotlib)





https://sci.nao.ac.jp/MEMBER/zenitani/openmhd-e.html

MHD equations

- Resistive MHD equations

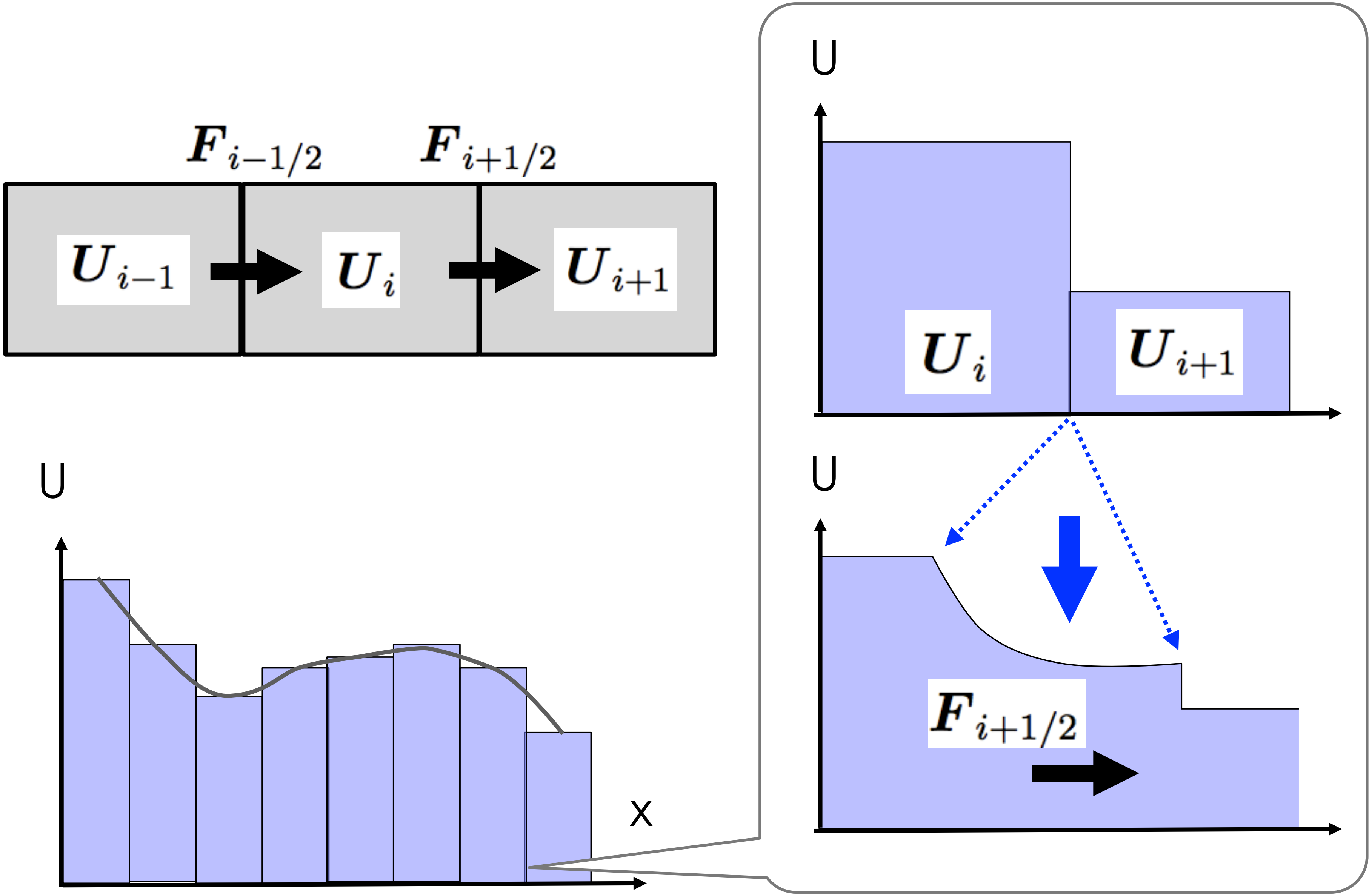
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0,$$
$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot (\rho \vec{v}\vec{v} + p_T \overleftrightarrow{I} - \vec{B}\vec{B}) = 0,$$
$$\frac{\partial e}{\partial t} + \nabla \cdot \left((e + p_T)\vec{v} - (\vec{v} \cdot \vec{B})\vec{B} + \eta \vec{j} \times \vec{B} \right) = 0,$$
$$\frac{\partial \vec{B}}{\partial t} + \nabla \cdot (\vec{v}\vec{B} - \vec{B}\vec{v}) + \nabla \times (\eta \vec{j}) + \nabla \psi = 0,$$
$$\frac{\partial \psi}{\partial t} + c_h^2 \nabla \cdot \vec{B} = -\left(\frac{c_h^2}{c_p^2} \right) \psi,$$

- Ohm's law

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{j}$$

- Hyperbolic divergence cleaning (Dedner+ 2002)
- Second-order TVD RK + Strang splitting

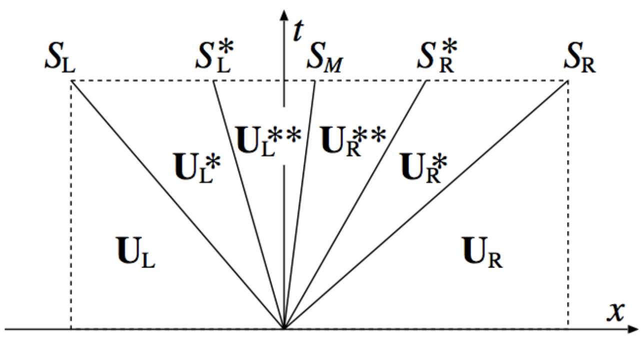
Riemann solver

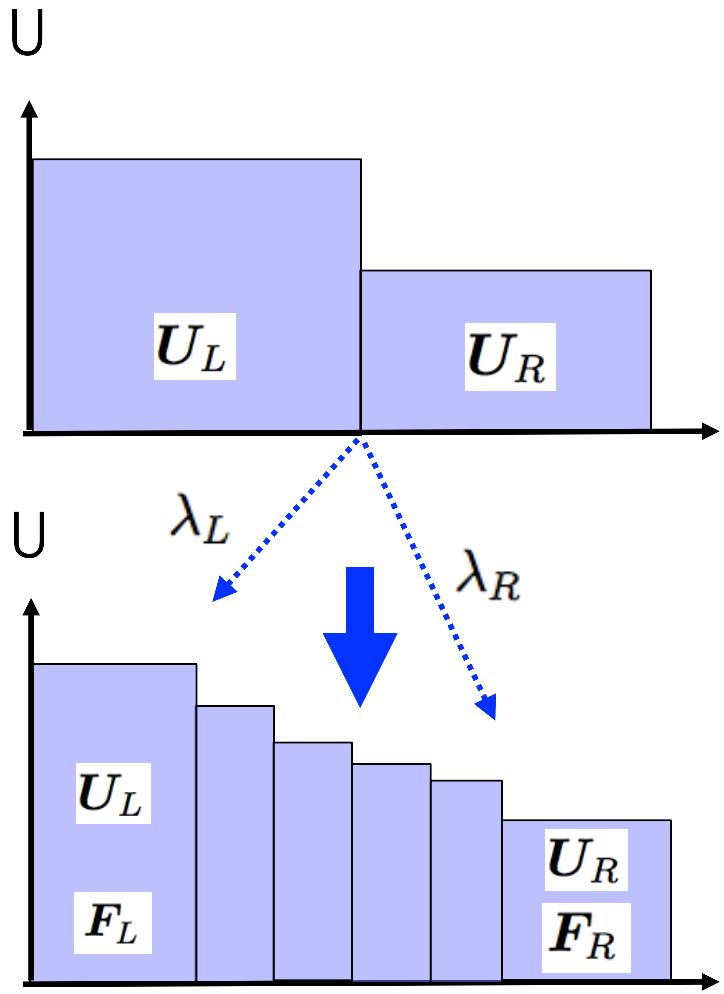


HLLD solver

- Proposed by Miyoshi & Kusano 2005
- An advanced variant of HLL solver

$$\mathbf{F}_{\mathrm{HLLD}} = \begin{cases} \mathbf{F}_{\mathrm{L}} & \text{if } S_{\mathrm{L}} > 0, \\ \mathbf{F}^{*}_{\mathrm{L}} & \text{if } S_{\mathrm{L}} \leqslant 0 \leqslant S^{*}_{\mathrm{L}}, \\ \mathbf{F}^{**}_{\mathrm{L}} & \text{if } S^{*}_{\mathrm{L}} \leqslant 0 \leqslant S_{M}, \\ \mathbf{F}^{**}_{\mathrm{R}} & \text{if } S_{M} \leqslant 0 \leqslant S^{*}_{\mathrm{R}}, \\ \mathbf{F}^{*}_{\mathrm{R}} & \text{if } S^{*}_{\mathrm{R}} \leqslant 0 \leqslant S_{\mathrm{R}}, \\ \mathbf{F}_{\mathrm{R}} & \text{if } S_{\mathrm{R}} < 0. \end{cases}$$

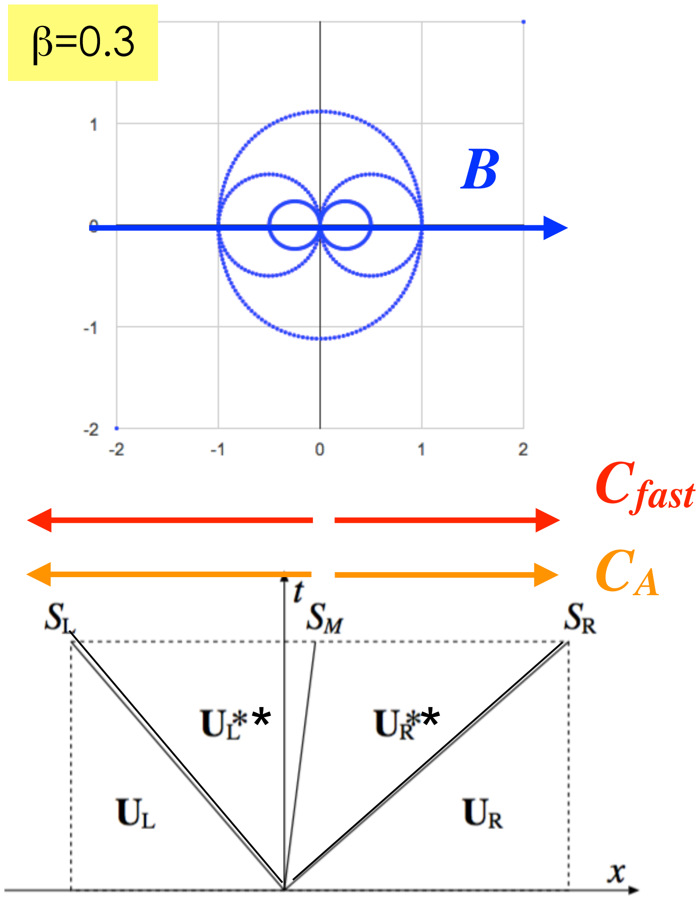


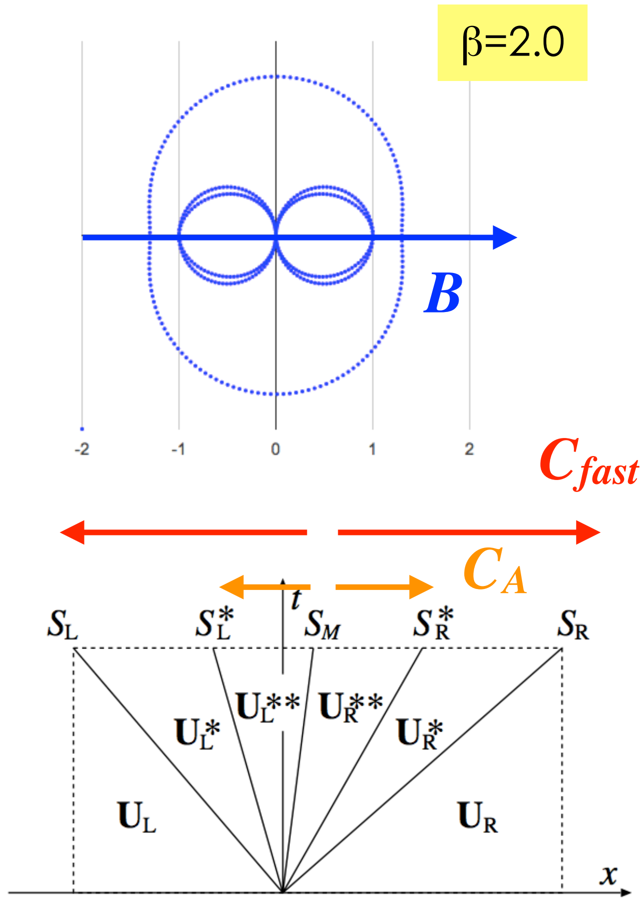


A problem in the HLLD scheme

- In the parallel direction, $C_A = C_{fast}$ for $\beta<1.2$.
- RD sometimes outruns the Riemann fan.
- We offer the problem parameters.

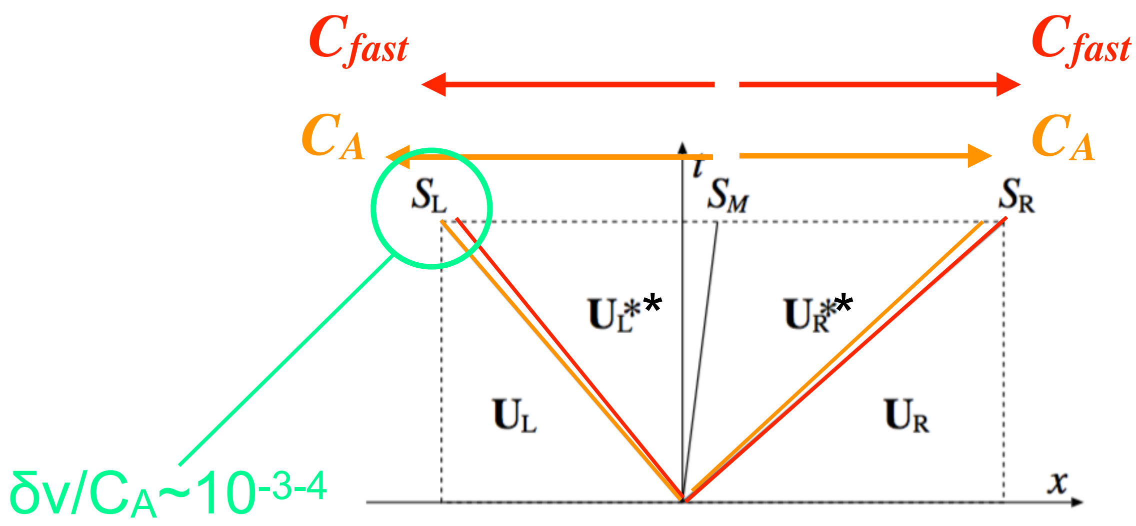
```
! left
  vx0 = -3.550886791794632E-002
  vy0 = 0.202198834859736
  vz0 = 0.d0
  pr0 = 0.573857561003025
  ro0 = 1.46274860814133
  bx0 = 1.d0
  by0 = 0.535958263440366E-004
  bz0 = 0.d0
! right
  vx0 = -3.563873070012032E-002
  vy0 = 0.201451798427819
  vz0 = 0.d0
  pr0 = 0.575034711174729
  ro0 = 2.46444099174925
  bx0 = 1.d0
  by0 = -4.588121811862009E-004
  bz0 = 0.d0
```





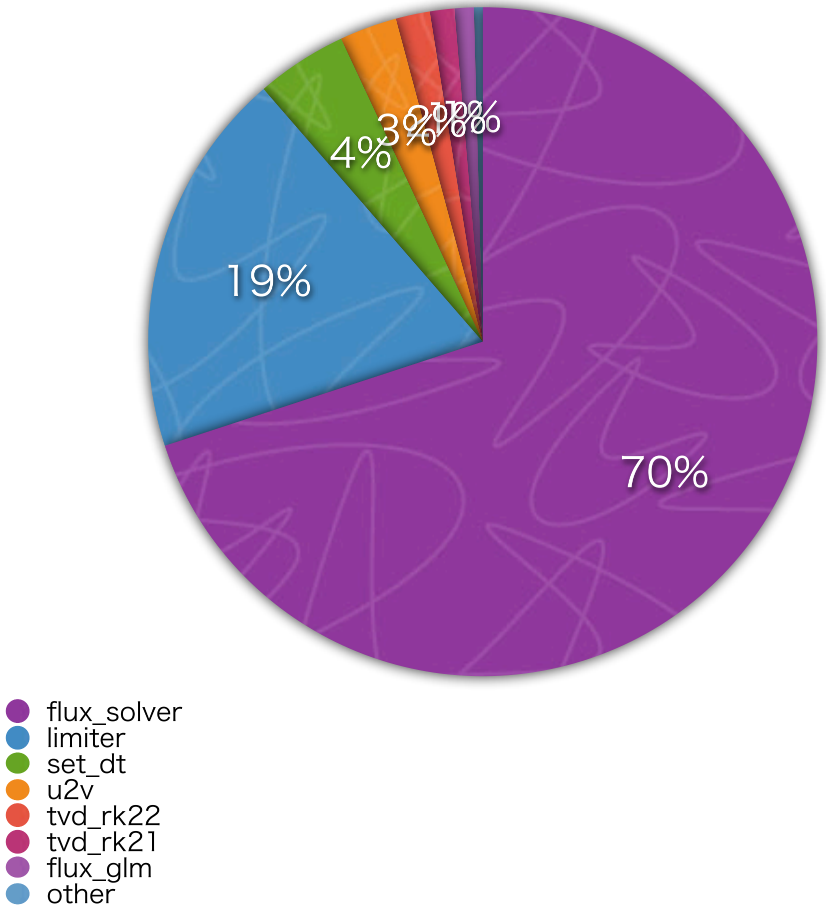
Solutions

- 1. HLLC=HLLD hybrid solver
  - Positivity
  - If clauses - not ideal for optimization
- 2. Faster C_{fast} (Miyoshi 2015 private comm.)
- 3. Adjust wavespeeds: `SL*=max(SL,SL*), SR*=min(SR*,SR)`
  - Good for optimization
  - Theoreticians are unhappy

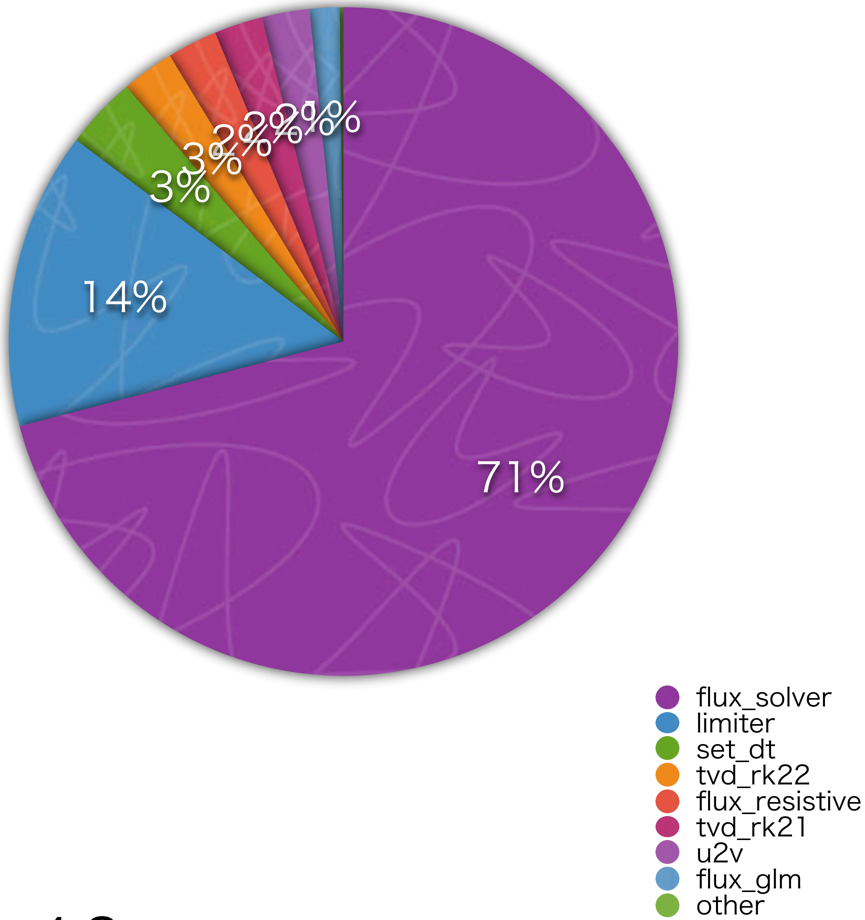


OpenMHD/2019 (HLLD) - Profiler output

Orszag-Tang vortex



Magnetic reconnection



gfortran 4.8

Performance tuning (1/2)

- Loop indexes
- Specifying `intent` attributes in subroutines
  - In particular, `intent(in)` and `intent(out)` work great.

```
subroutine bc(U,ix,jx)
  implicit none
  include 'param.h'
  integer :: ix, jx
```

→

```
subroutine bc(U,ix,jx)
  implicit none
  include 'param.h'
  integer, intent(in) :: ix, jx
```

- Reducing `if`-statements
  - This does not improve the performance on Intel computers, but it works well on FX computers
  - minmod limiter:

```
if( gA*gB .le. 0 ) then
   grad = 0.d0
else
   if( gA .gt. 0 ) then
      grad = 0.5d0 * min(gA,gB)
   else
      grad = 0.5d0 * max(gA,gB)
   endif
endif
```

→

```
grad = (sign(0.25d0,gA)
+sign(0.25d0,gB))*min(abs(gA),abs(gB))
```

  - MC limiter:

```
grad = (sign(0.5d0,gA)+sign(0.5d0,gB))*min(abs(gA),abs(gB),0.25d0*abs(gA+gB))
```

Performance tuning (2/2)

- Reducing square roots and divisions
  - [before] Fastest fast-mode speed

```
vfL = sqrt( ( (f1+B2) + sqrt(max( (f1+B2)**2-f2, 0.d0 ))) / ( 2*VL(i,j,ro) ))
vfR = sqrt( ( (f1+B2) + sqrt(max( (f1+B2)**2-f2, 0.d0 ))) / ( 2*VR(i,j,ro) ))
f1  = max( vfL, vfR )
```

  - [after]

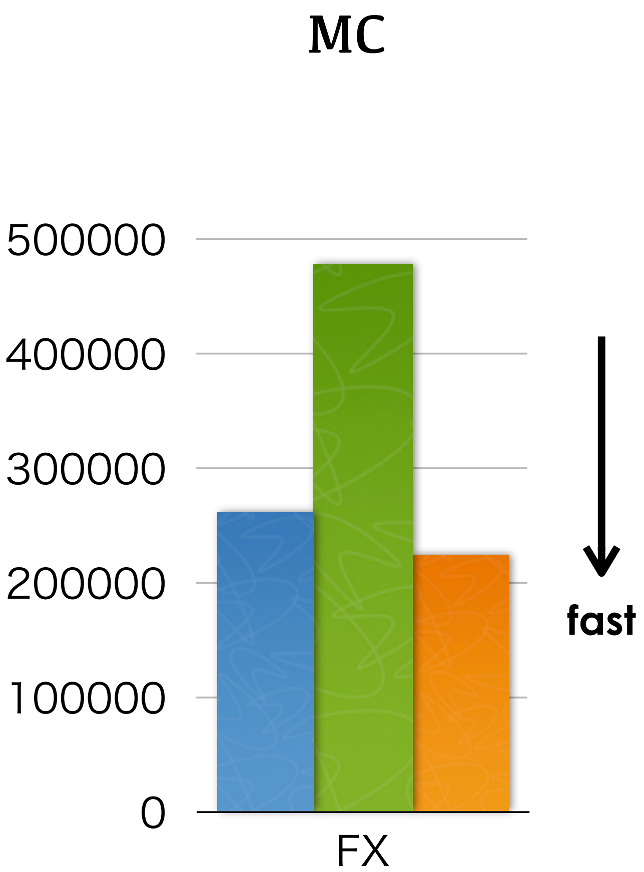
```
aL = ( (f1+B2) + sqrt(max( (f1+B2)**2-f2, 0.d0 ))) / ( 2*VL(i,j,ro) )
aR = ( (f1+B2) + sqrt(max( (f1+B2)**2-f2, 0.d0 ))) / ( 2*VR(i,j,ro) )
f1 = sqrt( max( aL, aR ) )
```

- Using register variables
- Using collapse option in OpenMP directives

```
!$omp parallel do private(i,j,k) collapse(2)
  do k=1,var1
     do j=2,jx-1
        do i=2,ix-1
```

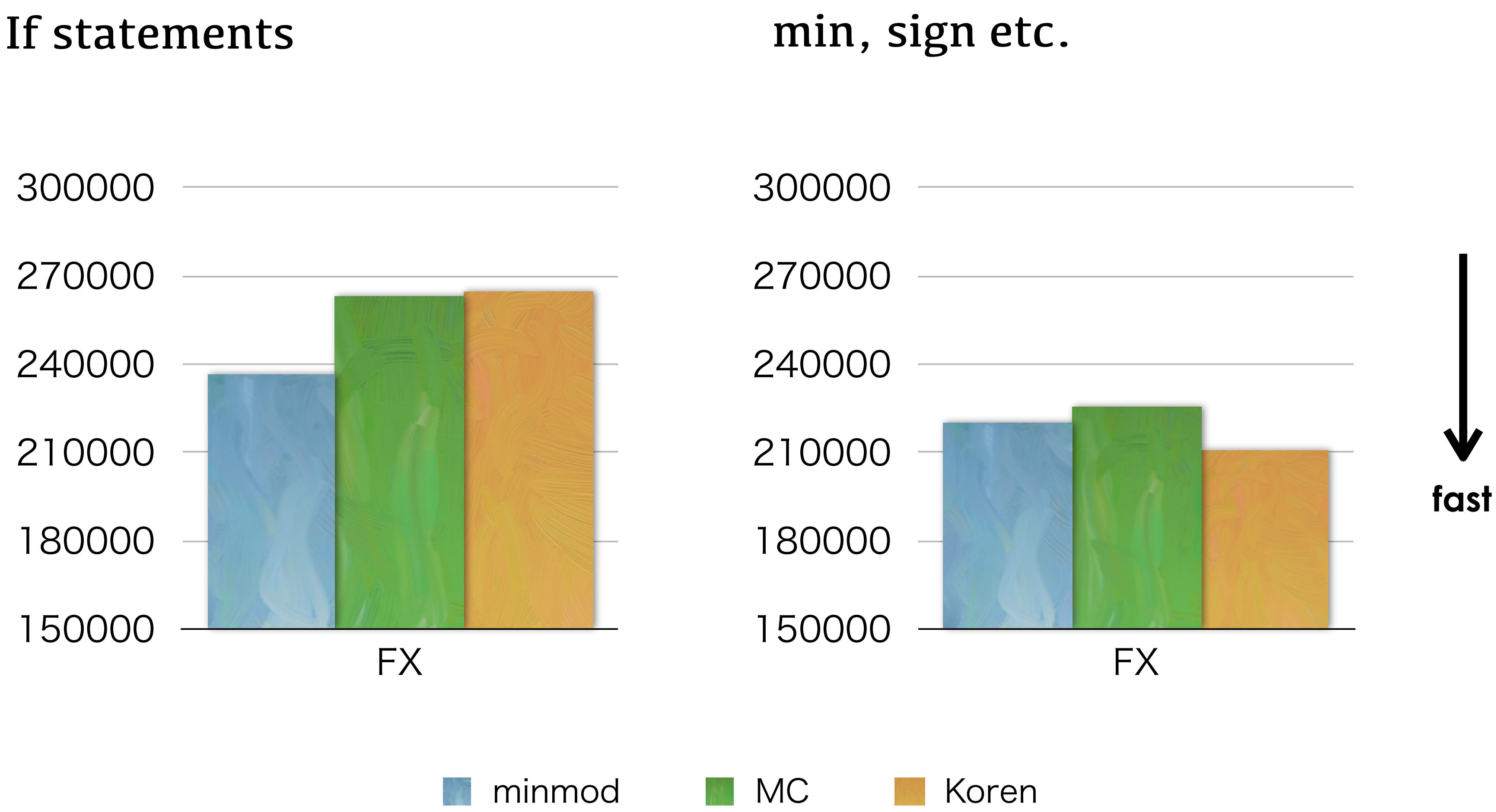
- Using good compilers
  - Intel Fortran compiler is usually better than gfortran
  - Gfortran 5.4 or 6.x is substantially better than gfortran 4.8

Improving performance - slope limiters

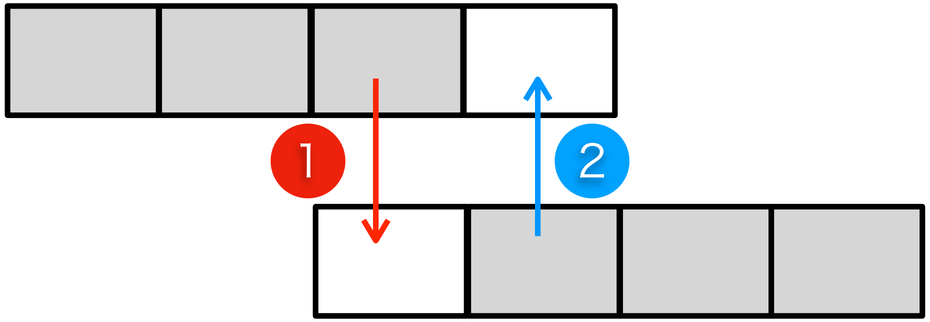



```
If statements
minmod(2a,minmod(2b,c))
(sign(0.5d0,a)+sign(0.5d0,b)) * min( abs(2a),abs(2b), abs(c) )
```

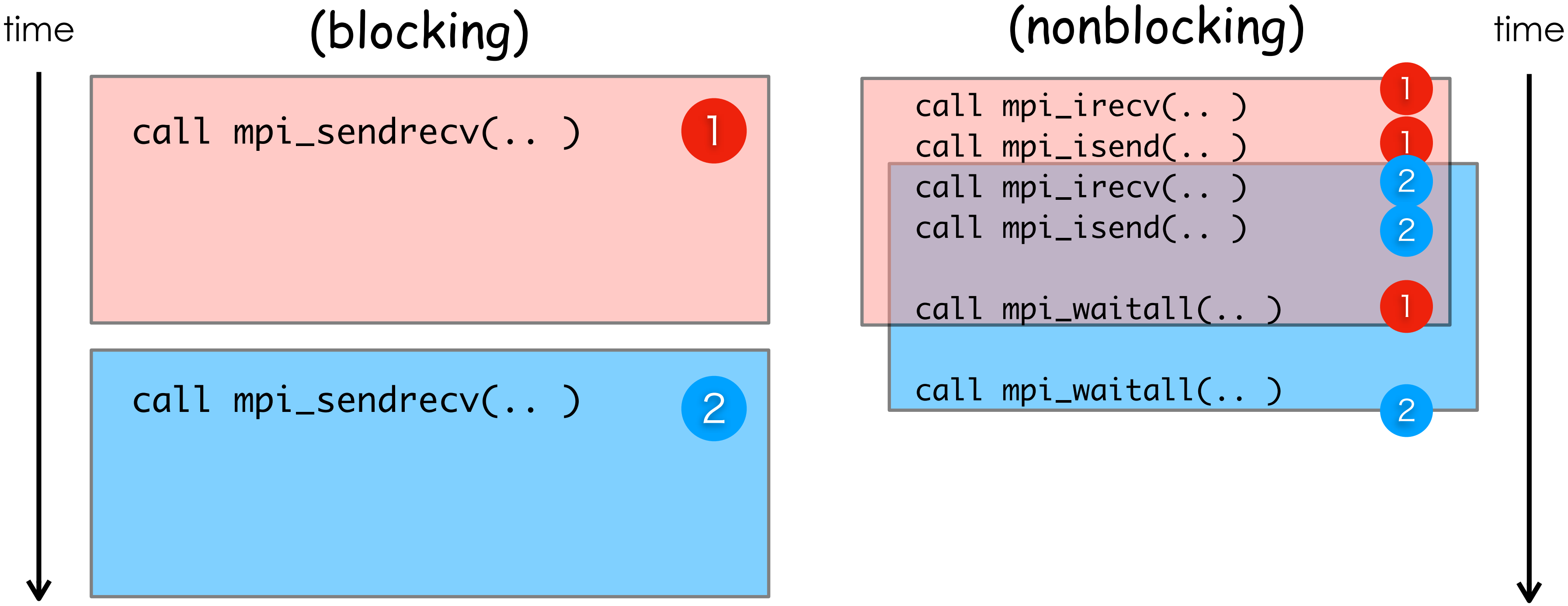
Improving performance - slope limiters



MPI nonblocking communication

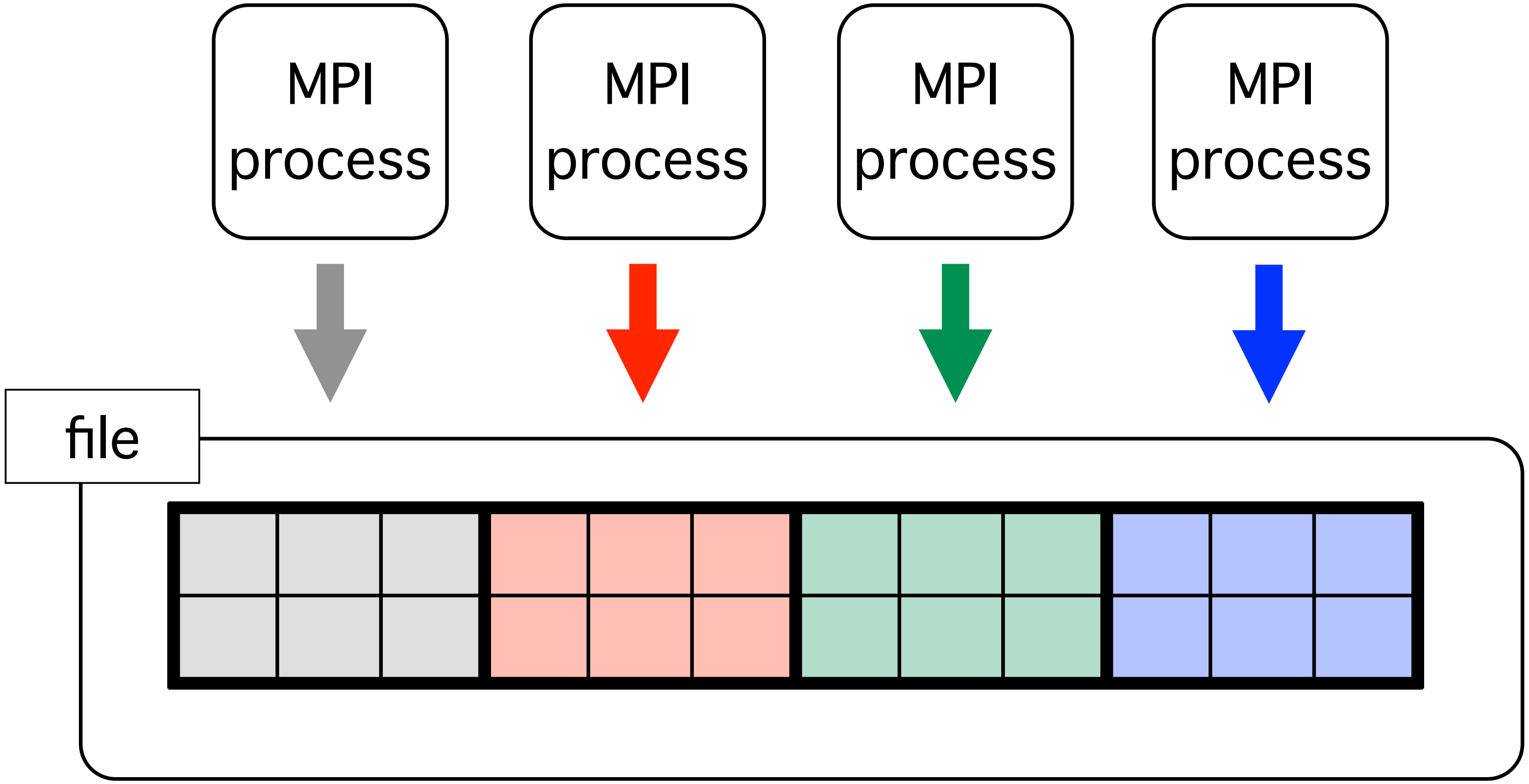


- Other operation while sending/receiving data (communication hiding)



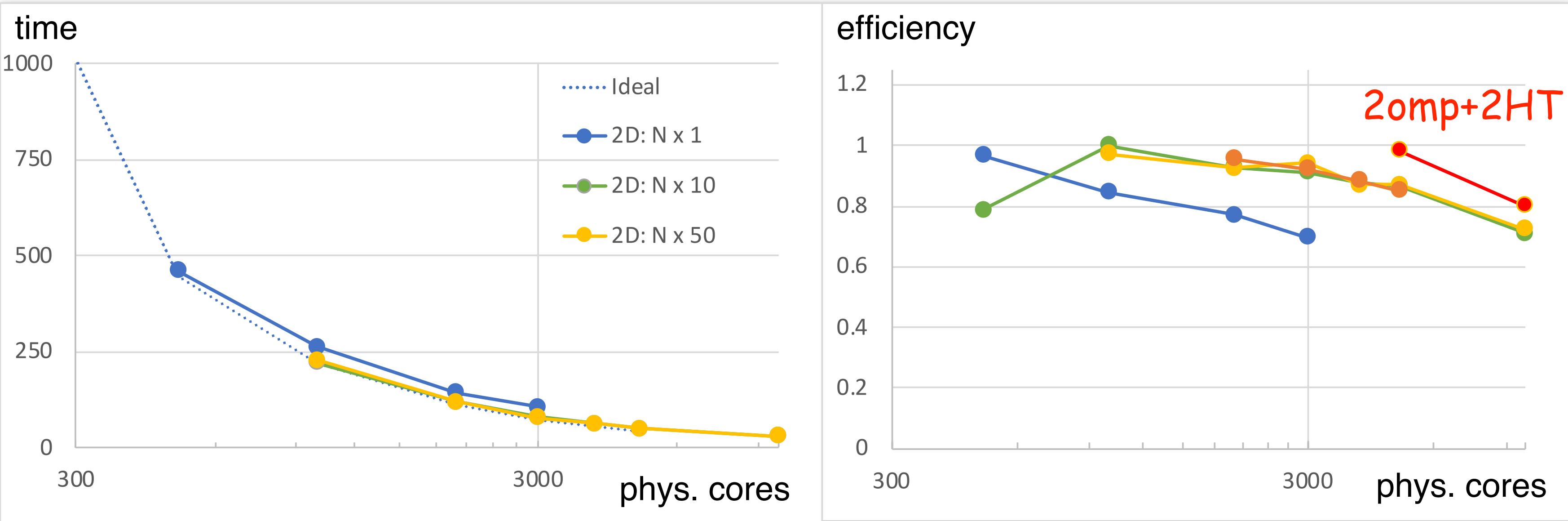
Parallel I/O (MPI-IO)

- Multiple MPI processes concurrently access data in a single file.
- The way to access the shared file is defined by `MPI_File_set_view`.



Parallel efficiency / strong scaling

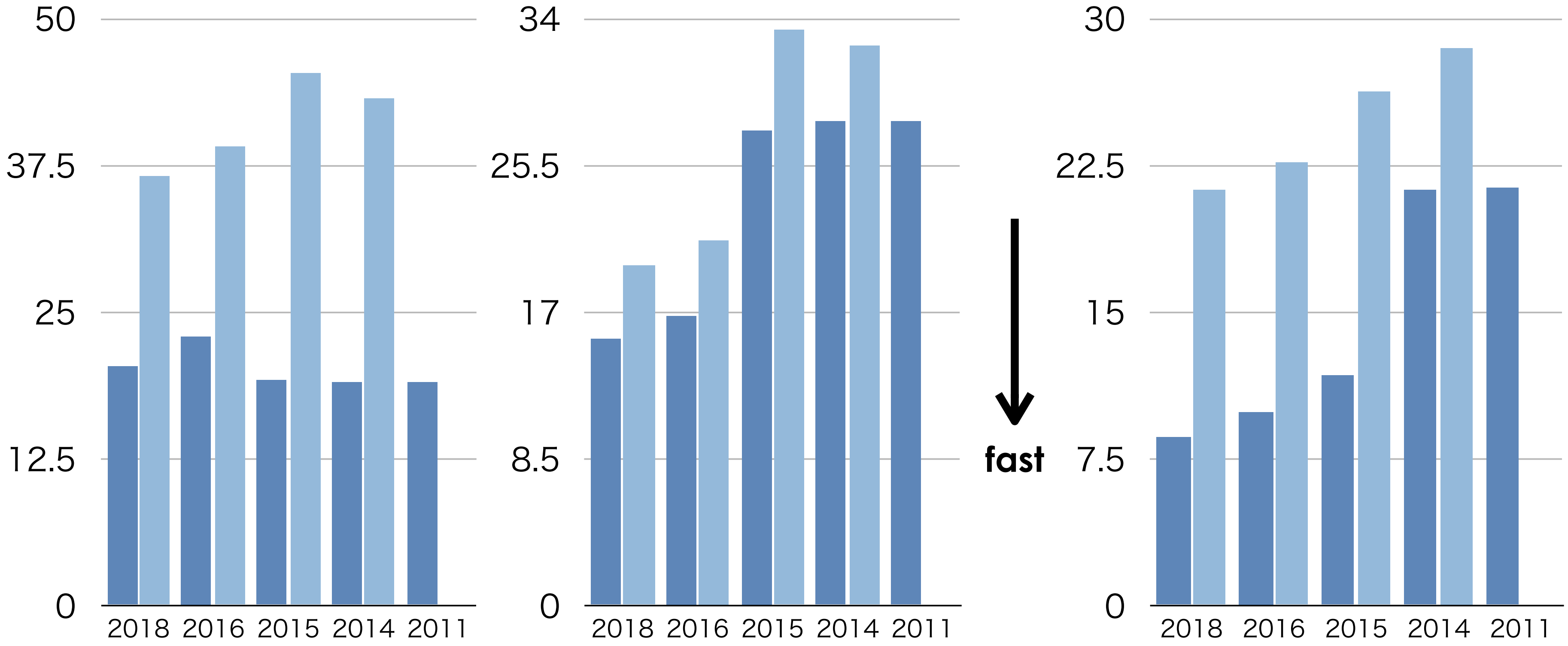
- Very nice scaling up to 5000 cores; moderate scaling at 10000 cores
- 94% efficiency at 3000 cores with flat MPI
- 98% at 5000 physical cores with hyperthreading (@Xeon Phi KNL)



OpenMHD/2019

Performance: years of improvement

KDK-A (Xeon Phi KNL) | NAOJ XC30 (Xeon) | JAXA FX100 (SPARC)



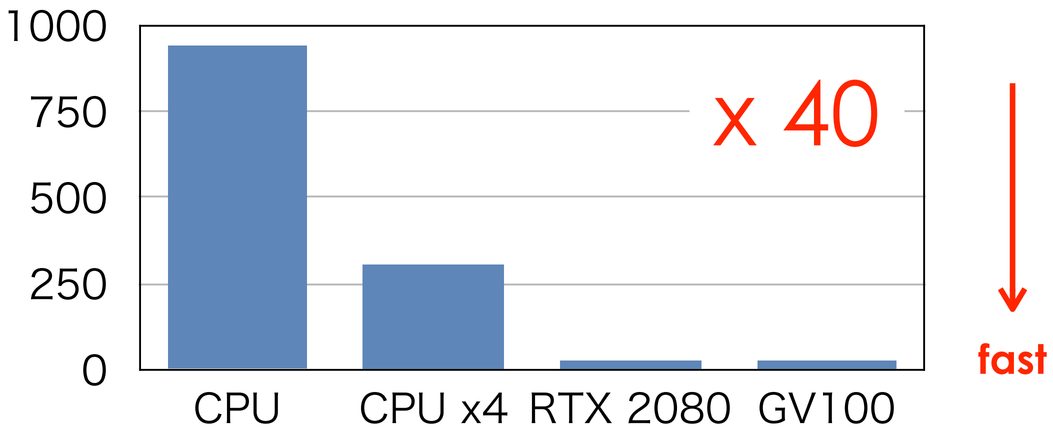
HLL/HLLD | HLL/HLLD | HLL/HLLD

Optimized for various CPU architectures

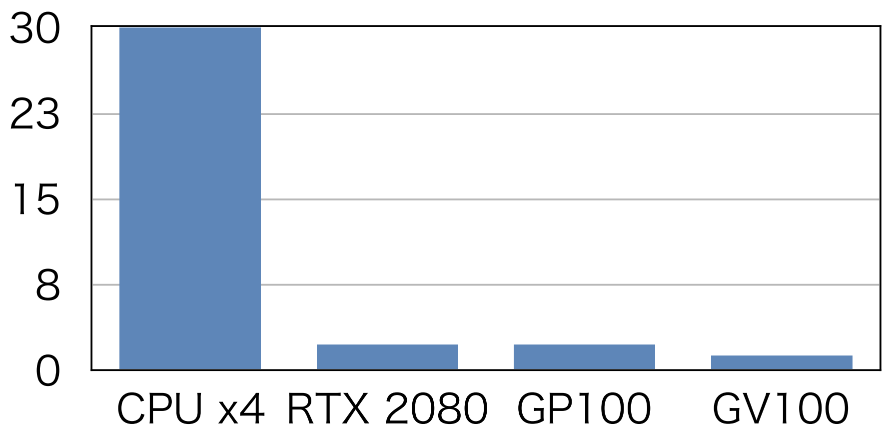
GPU version

- OpenMHD also runs on NVIDIA GPUs
- Partially written by CUDA Fortran

O-T vortex
800 x 800

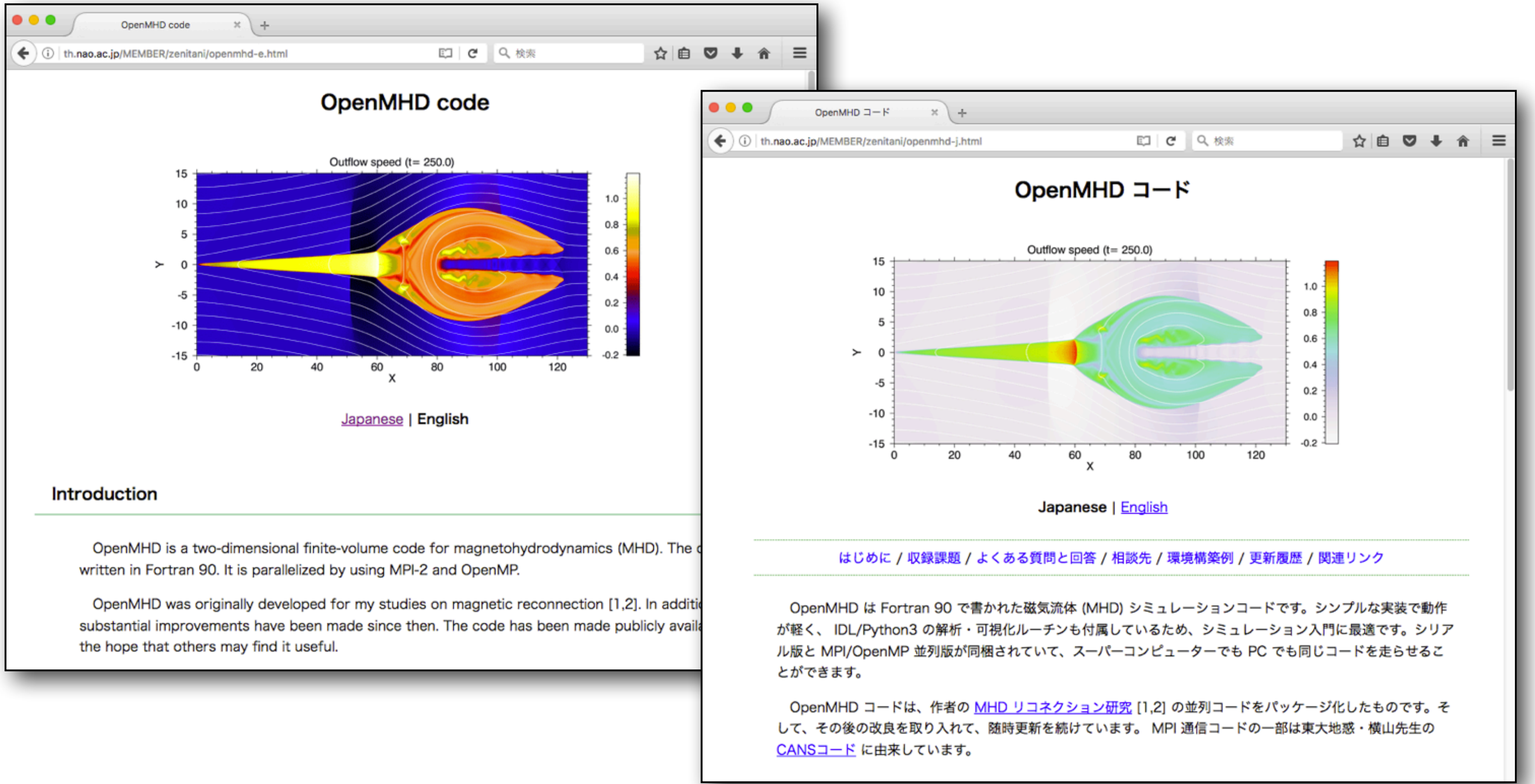


Magnetic
Reconnection
2000 x 500



Web site

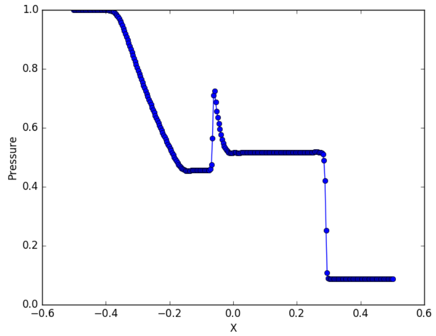
- Search “OpenMHD” with Google.
- Online documents [in Japanese]. English translation in progress.
- Gateway to a mailing list (41 users).

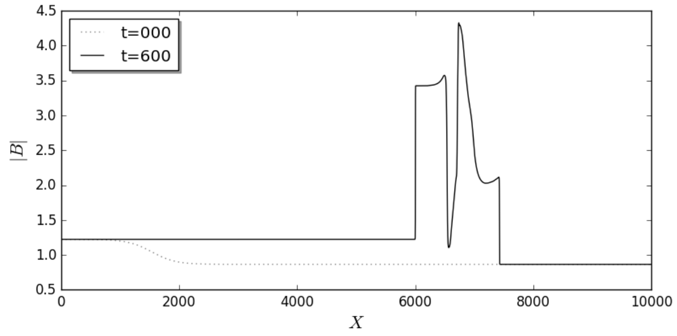


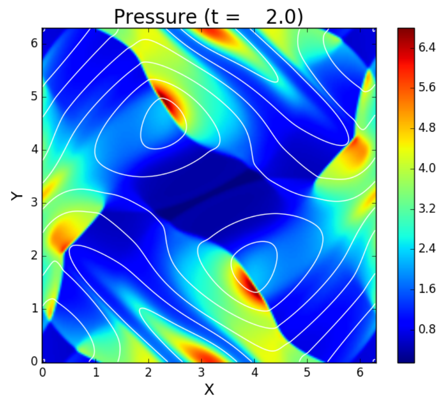
https://sci.nao.ac.jp/MEMBER/zenitani/openmhd-e.html

Built-in problems

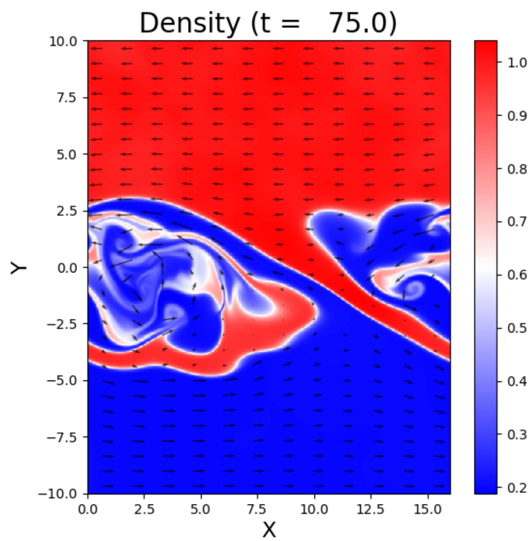
- Riemann problem
- Solar-wind problem
- Orszag-Tang vortex

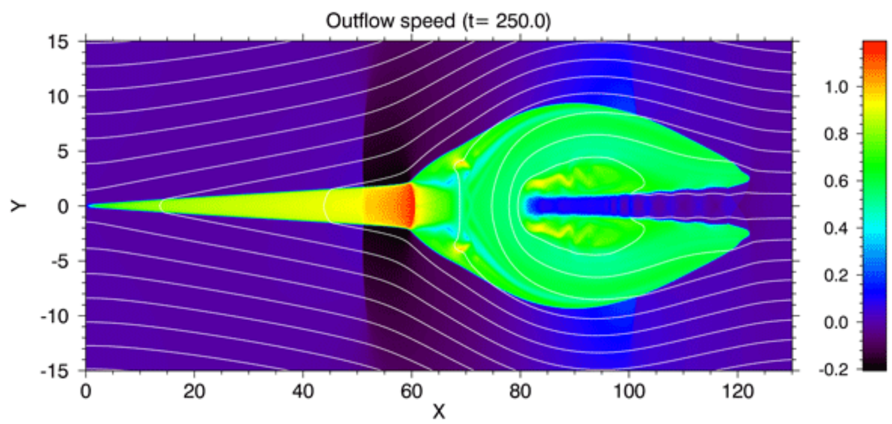






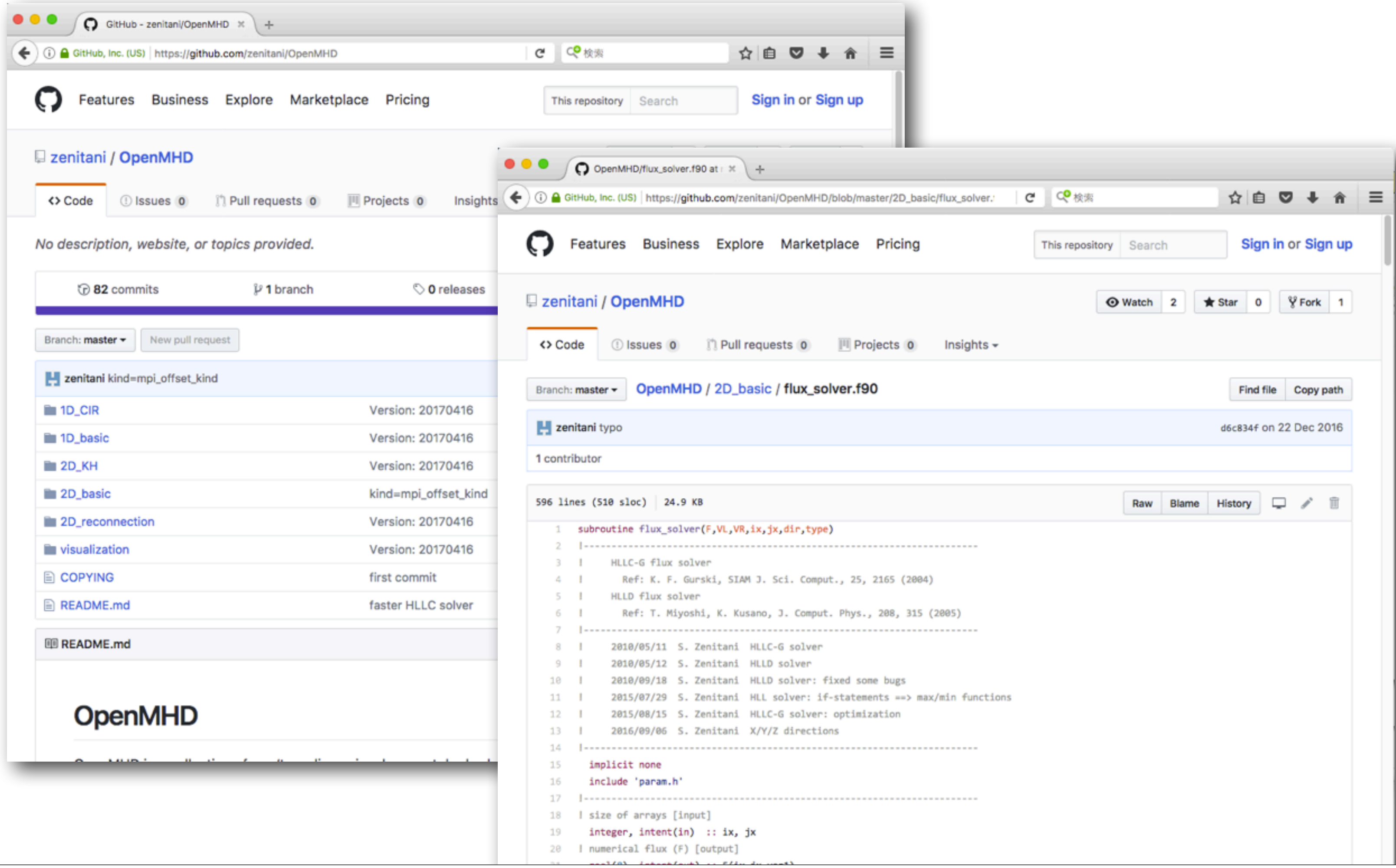
- KH & secondary instabilities
- Magnetic reconnection





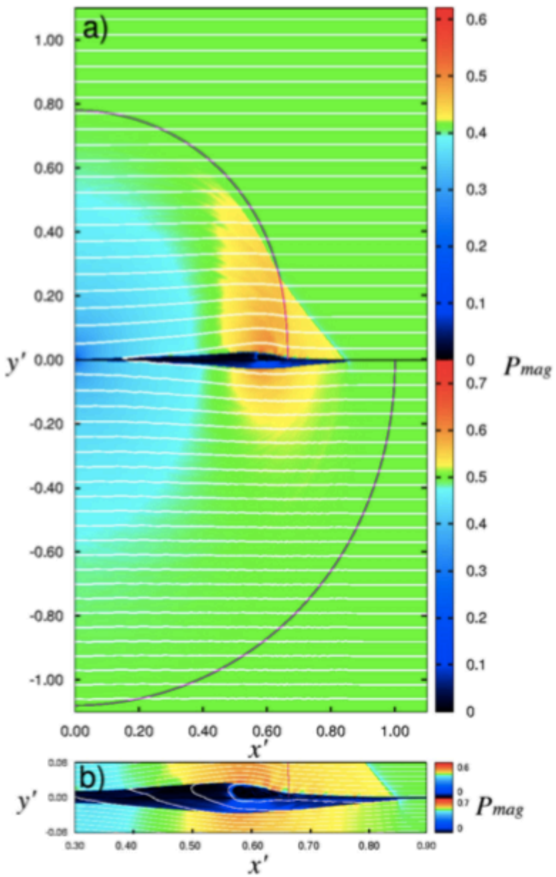
Source code management

- Our repository is hosted by GitHub.
- It is open to public -- pull requests are always welcome!

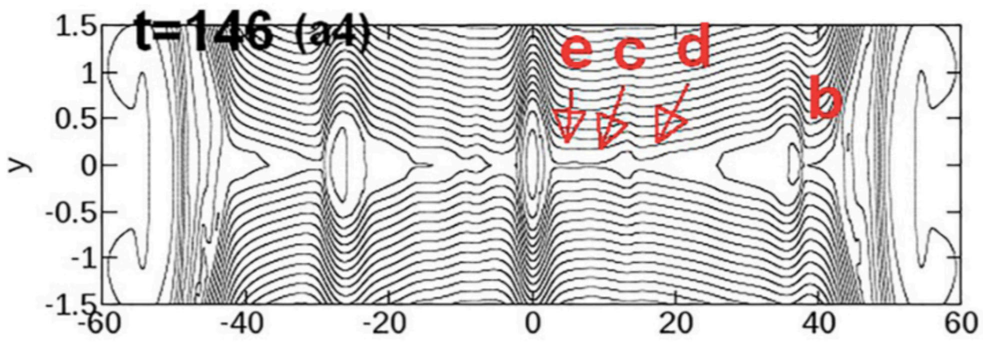


Research papers based on OpenMHD

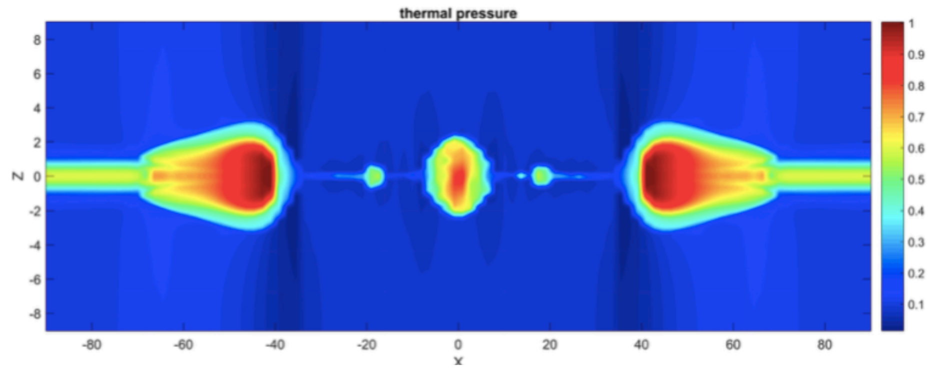
- Asymmetric reconnection
- Plasmoid-dominated reconnection



Nitta et al. 2016, 2019 ApJ



Shimizu et al. 2017 PoP



Hosseinpour et al. 2018 PoP

- Used in college & graduate school
- Kobe University and Ehime University

References

- [1] S. Zenitani & T. Miyoshi, *Phys. Plasmas* **18**, 022105 (2011)
- [2] S. Zenitani, *Phys. Plasmas* **22**, 032114 (2015)
- [3] A. Dedner et al., *J. Comput. Phys.* **175**, 645 (2002)
- [4] T. Miyoshi & K. Kusano, *J. Comput. Phys.* **208**, 315 (2005)
- [5] 銭谷誠司, 生存圏研究 13, 27 (2017)

URLs

- `https://ascl.net/1604.001`
- `https://github.com/zenitani/OpenMHD`
- `https://sci.nao.ac.jp/MEMBER/zenitani/openmhd-e.html`